Means for Risk Reduction & Analytical Approaches

Robert Smilowitz

Weidlinger Associates

New York • Cambridge • MountainView • Washington, DC • Santa Monica • Albuquerque • Edinburgh, UK

Design Approaches

- Goal to save lives
  - Reduce building damage
  - Preventing disproportionate collapse
  - Awareness of damage state by design professionals

Hazard Considerations

- Intentional or accidental explosion
- Vehicle or debris impact
- Fire
- Natural Hazard
- Faulty design or construction

Hazard Considerations

- Location on the site – accessibility to vehicle impact or standoff distance
- Plan Layout
  - Location of lobby, loading dock, underground parking
  - Regularity and continuity of structural grid
- Hazardous contents
  - Fuel storage and combustible content – influences fire intensity and duration

Design Principles

- No universal approach – case specific
- Failure will propagate vertically & horizontally away from initiating zone until
  - Failure is arrested -or-
  - Remaining structure becomes geometrically unstable

Design Principles

- Dynamic event
  - Different regimes
    - Initially impulsive
    - Subsequently oscillatory
    - Finally quasi-static
  - Differences in time scale may require different analytical models
- Different failure mechanisms for columns, walls, beams, slabs and connections.

Design Principles

- Propagation of failure front
  - Horizontally to beam/column or beam/wall interface
    - Flexural hinge – not likely to propagate across column line for structures with regular geometries
    - Shear failure
    - Axial failure (catenary)
  - Adjacent column must be able to receive dynamic effects (shear, thrust, moment & torsion) without failure

Design Principles

- Propagation of failure front
  - Release of compressive stress due to column failure – sends axial tensile wave through column line
  - Failure of connection of beams to vertical face of columns may arrest failure front (break away structure)
  - Failure of panel zone may reduce column capacity and promote propagation
  - If catenary forces develop
    - Connections must be able to transfer forces
    - Remaining structure must be able to resist forces.

Design Principles

- Structural Robustness
  - Redundant structures that provide alternate load paths in the event of a local failure
    - Interconnectivity between adjacent members through ties allows load redistribution throughout the structure
  - Shear strength that exceeds the ultimate flexural capacity of the member.
    - Avoid direct shear and punching shear failures.

Design Principles

- Structural Robustness
  - Ductility permits large deformations prior to failure.
    - Steels with high toughness
    - Maintaining overall structural stability
    - Connections between elements that exceed capacity of the members
    - Confinement of concrete structures
    - Continuity of reinforcement

Design Principles

- Structural Robustness
  - Capacity to resist load reversals
  - Reduced column spacing
    - enhance load redistribution
  - Shallow exterior bay
    - exposed to greatest hazard
  - Hardened transfer girders with large influence areas
    - require additional resistance to extreme events
  - Bearing walls and interior cross walls periodically spaced to enhance stability and arrest collapse

Design Principles

- Key Elements
  - Columns vulnerable to local events
    - Restrict access
    - Provide architectural enclosures
    - Design to span multiple stories
  - Load bearing walls vulnerable to standoff events
  - Spandrel beams at perimeter exposed to standoff events

Design Principles

- Indirect Methods
  - Prescriptive measures
  - Minimum standard
- Direct Methods
  - Specific Local Resistance
    - Local hardening to specified threat
  - Alternate Load Paths
    - Ability to bridge over initial damage zone
    - Notional removal of critical bearing elements

Indirect Design Approaches

- Prescriptive measures
  - easier to implement
  - uniformity of compliance
  - used extensively in UK and Eurocodes
  - NOT demonstrated to be effective through testing or analysis
- Seismic Details
  - Inherently ductile

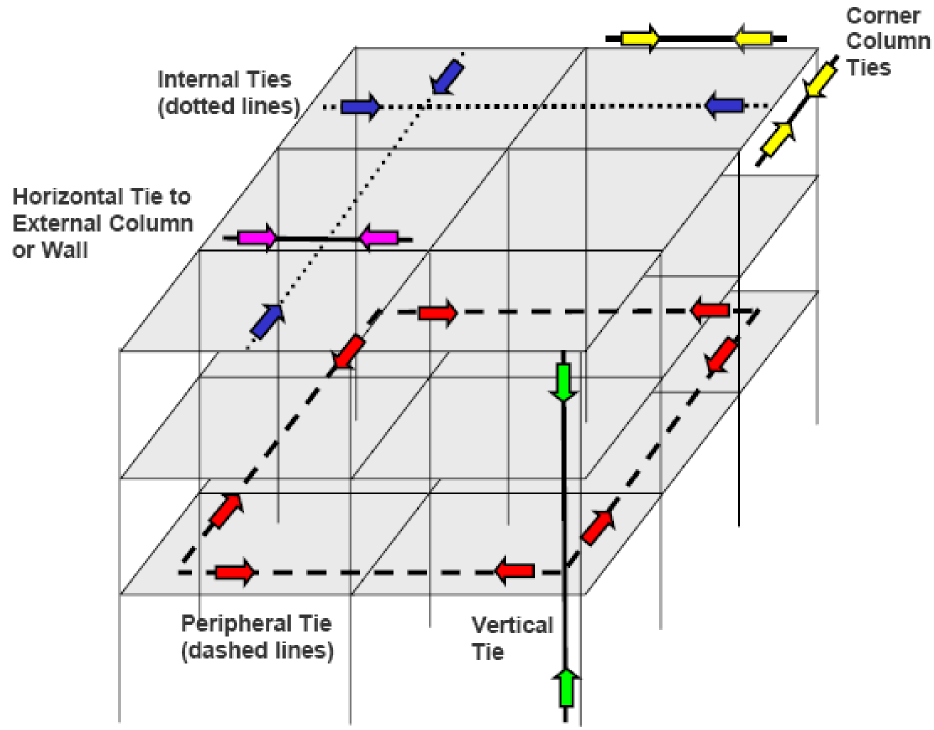
Indirect Design Approaches

- Returns on walls
- Changing span directions of floor spans
- Load bearing interior partitions
- Catenary action of floor slabs
- Beam action of the walls
- Redundant structural systems
- Ductile detailing
- Additional reinforcement for load reversals
- Compartmentalized construction

Indirect Design Approaches

- Tie Requirements
  - Key elements tied together
    - Peripheral – continuous around plan geometry to interconnect perimeter elements
    - Internal – continuous from one edge to the other in both directions
    - Vertical – continuous from lowest level to highest and spliced at third points of floor height
    - Horizontal – ties to edge columns and walls must be anchored into the structure in order to keep the edge elements vertical (minimize P-Δ effects)

Indirect Design Approaches



Different types of ties for structural integrity (DOD 2005)

Indirect Design Approaches

- Design strength with no other loads acting must exceed the required tie strength
- Load and Resistance Factor Design
  - Strength Reduction Factors Φ material specific code value
  - Over-strength Factors Ω account for excess strength above nominal design values

Indirect Design Approaches

- Tie Requirements
  - Concrete Structures
    - Reinforcement required for normal design may be considered for tie requirements
    - Adequately anchored
    - Continuous Bottom Reinforcement Over Supports
    - Confinement at Joints - Provides Ductile Behavior
    - Peripheral Ties at the Spandrels
    - Internal Ties through Floor Slabs and Beams
    - Horizontal Ties to Columns and Walls
    - Vertical Ties Along Perimeter Structure

Indirect Design Approaches

- Tie Requirements
  - Concrete Structures –
    - Over-strength Factors Ω for both concrete compressive strength and reinforcing steel yield & ultimate strength [UFC permits 1.25]
    - Strength reduction factors Φ for anchored, embedded or spliced reinforcement in tension 0.75 [ACI 9.3.2.6]
    - Splices - lapped, welded or mechanically joined with Type 2 mechanical splices
    - Splices - located away from joints and staggered

Indirect Design Approaches

- Tie Requirements
  - Concrete Structures –
    - Seismic hooks and development lengths required to provide anchorage
    - Internal ties anchored to peripheral ties at each end
    - Corner columns must be tied into the structure in both directions
    - Vertical ties tensile strength must exceed largest factored vertical load from any one story.

Indirect Design Approaches

- Tie Requirements
  - Precast Concrete
    - Tie anchors minimally capable of carrying dead weight of member
    - Ties lapped with bar in CIP concrete, topping or connecting concrete
    - Ultimate resistance of link equal to the ultimate tension in the tie
    - Compression and Shear

Indirect Design Approaches

- Tie Requirements
  - Steel
    - Ultimate and yield over-strength Factors Ω specific to grade of steel
    - Strength reduction factors Φ for members and connections
    - All tie connections must be capable of resisting tension forces
  - Masonry
    - Over-strength Factors Ω equal to 1.0
    - Peripheral horizontal ties
      - near edge slab
      - anchored

Indirect Design Approaches

- Composite construction
  - Must consider both requirements for Steel and Concrete components
    - Concrete deck on steel beam
      - Concrete deck – internal tie requirements
      - Steel frame – vertical, peripheral and external tie requirements

Direct Methods

- Analytically determine resistance
  - Specified event – designs critical load bearing elements to resist design basis event. Prevents the removal of critical element.
  - Nominal removal of critical element – Alternate load path method for threat independent design. Doesn’t account for the damage to surrounding structure due to the element removal.

Direct Methods

- Analysis Techniques
  - Small deformation
    - Deformed configuration may be represented by its original geometry
    - Conventional definitions of stress and strain
    - Does not represent geometric stiffness or buckling
  - Linear elastic constitutive models
    - Simplest and most widely used
    - Does not account for yielding of materials

Direct Methods

- Analysis Techniques
  - Nonlinear
    - Yielding of materials and permanent deformations
    - Geometric stiffening due to axial tension
    - Buckling due to axial compression
    - Connection details
      - Explicit representation of connection detail
      - Equivalent Force-Displacement and Moment Curvature relationship using nonlinear springs

Direct Methods

- Performance Criteria
  - High Performance
    - collapse does not initiate either due to local hardening or successful redistribution of loads
  - Acceptable Performance
    - collapse limited to bay where initial damage is assumed to occur, within one floor above or below initiating damage
    - deformations limited to a faction of the story height.
  - Limiting deformations must be consistent with the precision of analytical methods
  - Must account for capacity of existing structures

Direct Methods

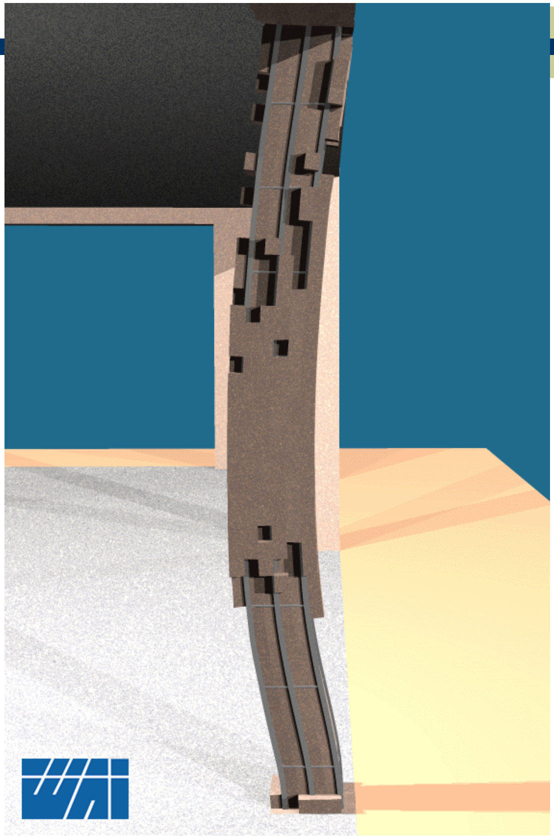
- Specific Local Resistance
  - Rational Design Approach
    - Prevents Initiating Damage
      - Key elements
      - Transfer structure
    - Ductile detailing
    - Use appropriate analysis methods
      - Explicit Finite Element analysis

Direct Methods

- Specific local resistance
  - Determine Loads to Resist
    - Analyze for Multiple Abnormal Loadings
      - Site Specific Threat - Hardened column is capable of sustaining blast environment that would fail un-hardened counterparts
      - Standoff Threat - Balance Capacity of Vulnerable Members to Capacity of Adjoining Beams and Columns
      - Satchel Threat – Balance Capacity of Vulnerable Columns to Resist Magnitude of Explosive that Could be Distributed to Multiple Un-Hardened Columns

Specific Local Resistance

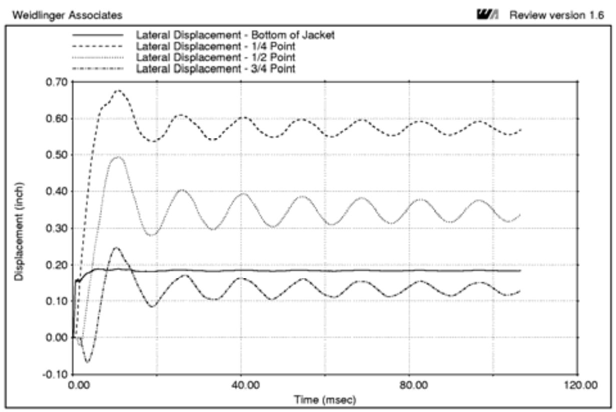
DB6 Test

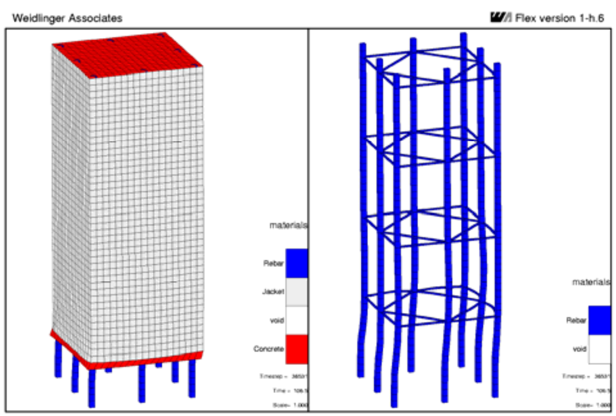


Pretest Calculation

Specific Local Resistance

Jacketed





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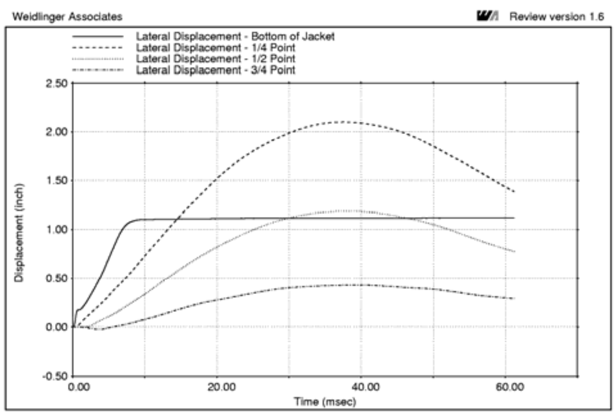
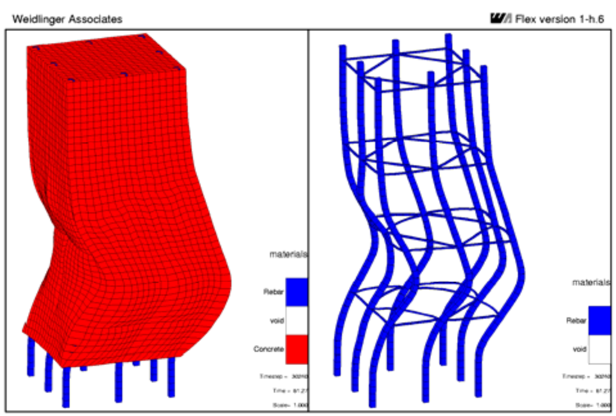




Direct Methods

- Alternate Path Methods
  - Determines structures ability to withstand removal of critical member
  - Does not consider actual conditions causing the removal of critical member or any damage to adjoining structure associated with the removal of critical member
    - Satchel threat may be placed against multiple columns
    - Standoff threat may damage adjacent structure
    - Results in oversized beams relative to the columns

Direct Methods

- Alternate Path Methods
  - Analytical approaches
    - Hand Calculation
    - Static Elastic Analysis
    - Static Geometrically Nonlinear Inelastic Analysis
    - Dynamic Elastic Analysis
    - Dynamic Geometrically Nonlinear Inelastic Analysis

Direct Methods

- Alternate Path Methods
  - Analytical approaches
    - Elastic Static
      - Amplified load to approximate dynamic effect
      - Amplified demand capacity ratios to approximate nonlinear behavior
      - Does not account for redistribution of forces, P-Δ instability, or the development of catenary or membrane modes of resistance
      - Subjective method for defining extent of continuity or ductility and equivalent to indirect methods

Direct Methods

- Alternate Path Methods
  - Analytical approaches
    - Inelastic Static
      - Amplified load to approximate dynamic effect and applies gravity load in increments (push-down)
      - Geometric non-linearity accounts for tension membrane stiffening
      - Inelastic material properties account for yielding
      - More accurate representation of member and connection forces
      - Indicates instability associated with large deformations

Direct Methods

- Alternate Path Methods
  - Analytical approaches
    - Inelastic Dynamic
      - Three dimensional explicit, nonlinear large displacement transient analysis produce most accurate predictions of progressive collapse
      - Most computationally intensive
      - Requires experienced modelers and analysts
      - Justification based on most cost effective structural solution

Direct Methods

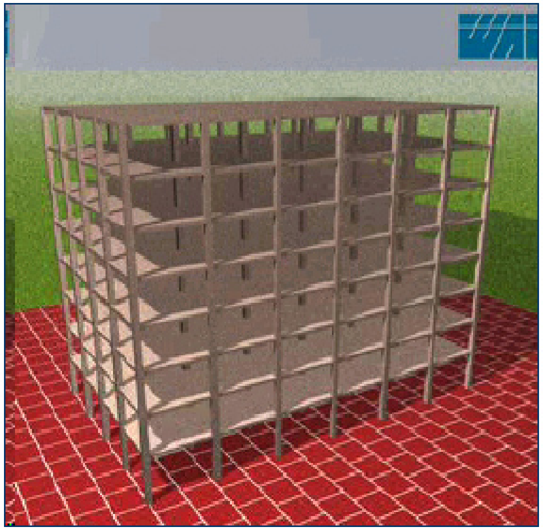
- Analytical Approaches
  - The addition of each level of analytical rigor:
    - reduces the level of simplifying assumptions
    - increases the level of expertise required to model the structure
  - Analytical results, based on simplifying assumptions, require interpretation
    - Demand Capacity Ratios
    - Ductility limits

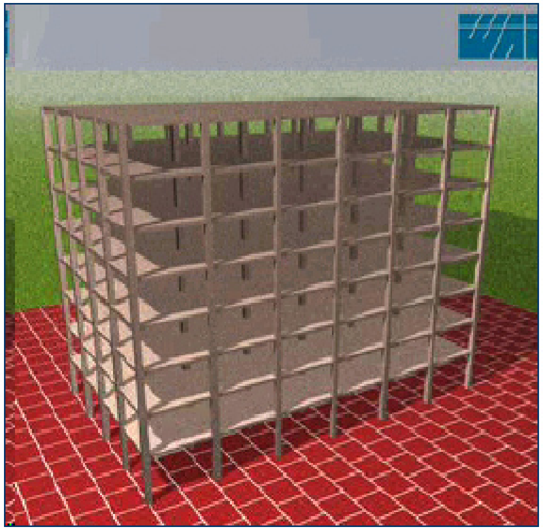
Direct Methods

- Analytical Approaches
  - Research is needed to determine appropriate performance criteria
    - Relating elastic response analyses to inelastic behavior
  - Tests on real structures are needed to validate simplified methods
    - Instrument pre-demolition tests

Examples Of Progressive Collapse Simulations

- Typical Reinforced Concrete Flat Plate Structure

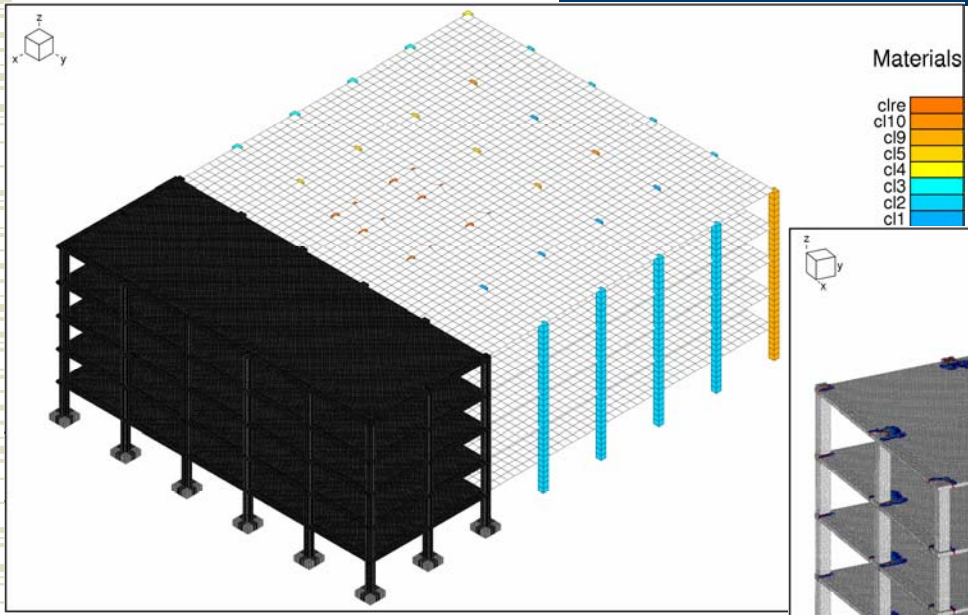


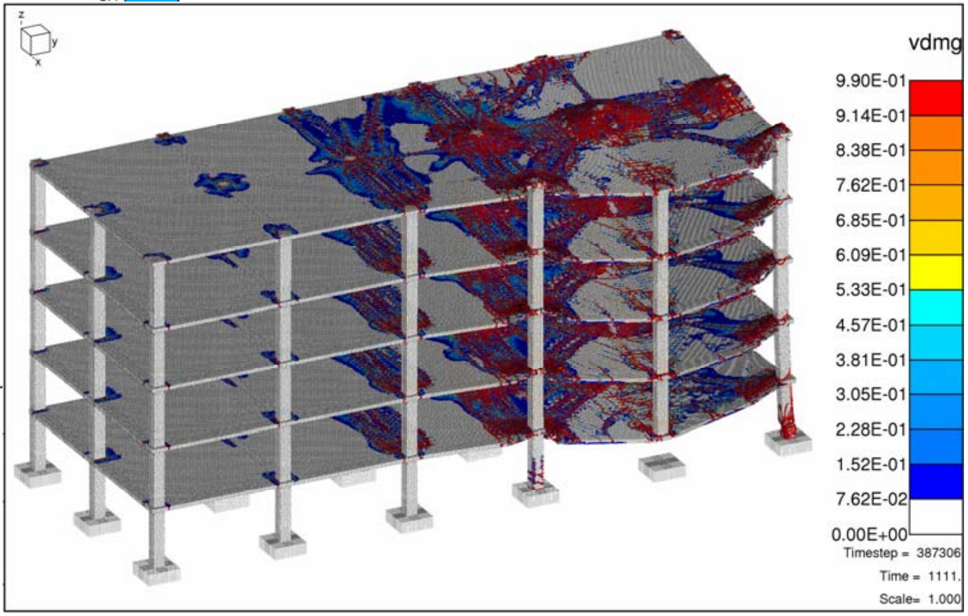


Long side

Short Side

Examples Of Progressive Collapse Simulations





Concrete Damage

UFC Guidelines

- Very Low Level of Protection
  - Prescriptive tie forces - horizontal ONLY
    - Revise structural system if required tie forces cannot be developed
- Low Level of Protection
  - Prescriptive tie forces – horizontal & vertical
    - Alternate Path where adequate vertical tie forces cannot be developed

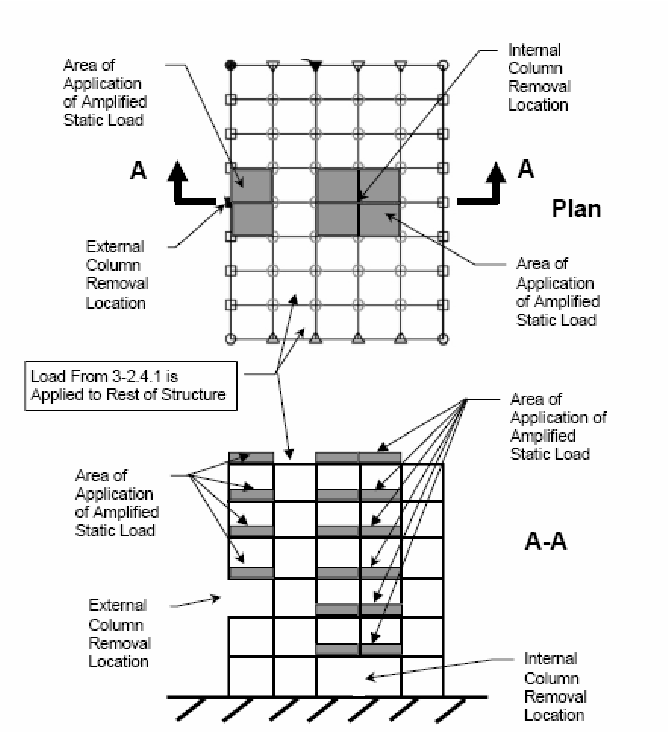
UFC Guidelines

- Medium and High Levels of Protection
  - Prescriptive tie forces – horizontal & vertical
    - Alternate Path where adequate vertical tie forces cannot be developed
    - Redesign if inadequate horizontal tie force capacity (Alternate Path cannot be used to justify design)
  - Alternate Path
    - Individual column removal for all representative perimeter columns for each floor (internal columns at uncontrolled spaces or parking) one at a time
    - Redesign all similar conditions if Alternate Path method cannot be shown to work
    - Peer Review required
  - Additional ductility
    - shear capacity greater than flexural capacity for all ground floor, perimeter columns & load bearing walls

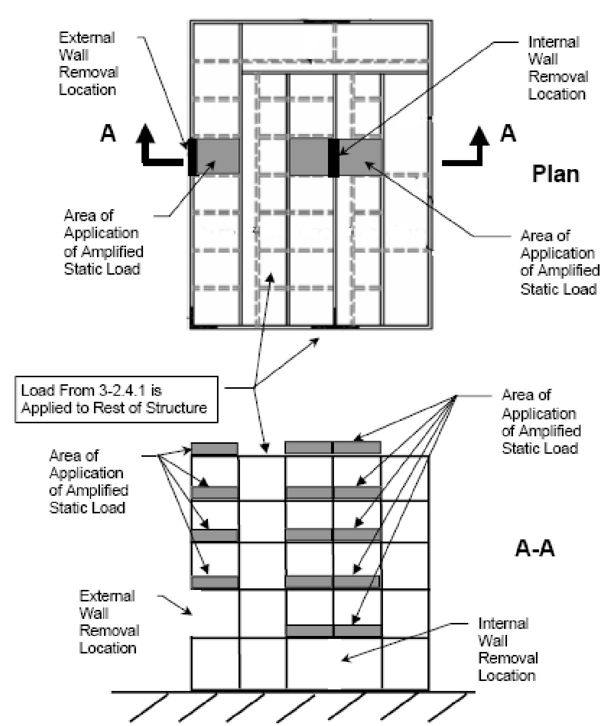
UFC Guidelines

- Double effective height for columns and load-bearing walls
- Load Combinations for Alternate Path analysis
  - Nonlinear Dynamic (0.9 or 1.2)D + (0.5L or 0.2S) + 0.2W
  - Linear and nonlinear Static 2.0[(0.9 or 1.2)D + (0.5L or 0.2S)] + 0.2W
- Strength reduction and over-strength factors
- Uplift loads on floors and slabs (one bay at a time)
  - Net upward load 1.0D + 0.5L
- Reinforce external masonry walls
  - Vertical and horizontal reinforcement

UFC Guidelines



Column Removal



Wall Removal

UFC Guidelines

- Acceptability Criteria
  - LRFD
    - LRFD Design Strength > Required Strength
    - Strength reduction and over-strength factors
  - Deformation Limits
    - developed by ACOE-PDC (Omaha)
  - Collapsed area of floor directly above removed support must be less than the smaller of:
    - 1,500 ft^2 (internal column) & 750 ft^2 (external column)
    - 15% (internal column) & 30% (external column) of the total area of that floor

GSA Guidelines

- Consider only steel and reinforced concrete
- Based on Alternate Path Method
  - Applied to ground floor perimeter columns
    - Static Analysis 2.0(1.0D + 0.25L)
    - Dynamic Analysis 1.0D + 0.25L
- Demand Capacity Ratios – Linear Analysis
  - NO strength reduction factors
- Deformation limits – Nonlinear Analysis
  - developed by ACOE-PDC (Omaha)

GSA Guidelines

- Damage limited to the smaller of
  - the structural bays directly associated with removed column or wall
  - 1,800 ft^2 on the floor above the removed column or wall

Screening Tool

- General Purpose Approach
  - Structural dynamics
  - Nonlinear analysis
  - Global and local modeling
  - Evaluation of initial damage region

Screening Tools

- Four step process
  - Evaluate the performance of column in response to blast loading (skip if threat independent)
  - Evaluate potential for failure front to propagate to adjoining beam and adjacent column
  - Investigate potential for adjacent column to resist additional loads
  - Investigate global stability of the structure

Phases of Progressive Collapse